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The Design and Construction of Apparatus for Operating Brown's Drum-Spring Testing Device. And the Investigation of Indicator Drum-Springs on the Same.

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W. I. A. Sc. C. E. Univ. 4 June '46

I The Object.

The object of this thesis was first to design and construct a self contained machine to run the Brown's drum-spring testing device. And then to investigate by means of this device the drum springs of three types of modern indicators. And determing for each what would be the best speeds to run the engine at, for given tension on the drum springs.

II The Theory Relating to Drum Springs.

Before starting to design the different parts of the machine, it would be best to look up as much of the theory relating to drum springs as we can find on the subject. And thus have a clear idea what we want in designing the apparatus. And also to get the theory of the of the method upon which the testing of the springs would be based.

(a) Accuracy of the drum motion.

(From A. S. M. E. vol 14) by J. B. Webb.

The accuracy of the drum-motion depends on the form of the drum spring, the mass moved, the length of the diagram, the elasticity of the connecting cord, and the method of connecting drum to engine. The last of these is mainly a geometrical question, which will not be discussed here.

"Now it is necessary to the ideal action of the drum, that its natural speed of oscillation should agree properly with the speed of the engine, and every drum and spring have their own period of oscillation to ascertain this, the spring should be made fast to drum, instead of being simply hooked to it, and the drum should be mounted upon centres so that it may oscillate with little friction. When the spring and drum are so proportioned to each other that they have the same time of oscillation as the engine, the motion of the drum, if there be no friction, will agree with the motion of

the engine; i.e., the drum will reverse at exactly the same instant as the engine does, and a cord conveying motion to the drum will remain uniformly stretched, so that there will be no change of amplitude.

The natural time of oscillation is the same whether the spring is attached firmly to the drum and the drum be free to oscillate unconfined by a cord, or whether the spring be hooked to the drum and the latter drawn permanently out of its position of rest by a tightly stretched cord.

To make this clearer, suppose a simple mass m

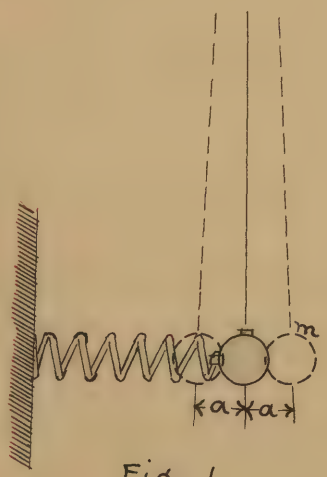


Fig. 1.

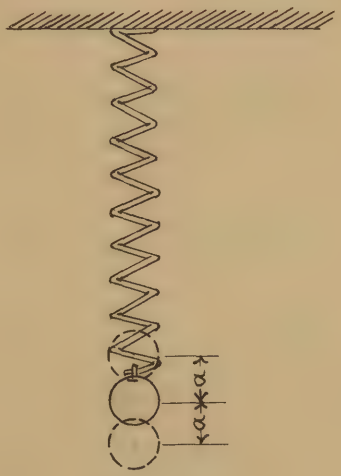


Fig. 2.

Fig. 1, attached to a spring and supported by a long string, so that it is free to oscillate horizontally uninfluenced by gravity. If the mass be now drawn a distance a to the right and set free, it will oscillate, under the action of the spring, between two positions equidistant from and on opposite sides of its central position, or position of rest, and the distance 2a between these two extreme positions is the amplitude of its oscillation. Call the time or period of its complete oscillation t, i.e., - the time required for its return to the position at which it was set free. Suppose again that the same mass be suspended from the ceiling by the same spring, as in Fig. 2, the weight of the mass will stretch the spring as shown, and if the mass be supposed to be a unit mass, the tension in the spring will be about 32 lbs., whereas in the central position in Fig. 1 the tension is zero. Now

let the suspended mass be either raised or pulled down a distance a from its natural position and set free, it will vibrate vertically, precisely the same as it before vibrated horizontally, i.e., the time t will be same and the amplitude $2a$ the same. Suppose that in Fig 1 the tension of the spring when extended a to the right is 10 lbs., and when compressed a to the left, -10 lbs., the minus sign indicating that the tension is compression, then at intermediate points the force of the spring will be proportionate to the distance of the mass from its central position. The same is true when the mass is suspended, except that all the tensions must have 32 lbs. added to them, so that at the extreme upper position the tension of the spring is $32+(-10)=22$ lbs. at central point $32+(0)=32$ lbs. at the lowest point, $32+10=42$, and at any intermediate position, $32+$ an amount proportionate to the distance

of the mass below its central position, distances above this position being regarded as minus.

Suppose in third case that the mass and spring are arranged to oscillate horizontally. See Fig. 3

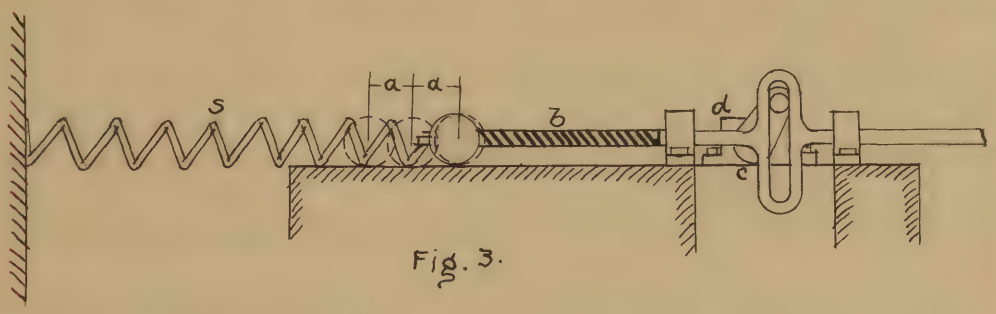


Fig. 3.

In which the mass is supposed to be supported by a frictionless plane, instead of being suspended as in Fig 1. And mass is drawn out of its central position by a constant force of 32 lbs. as in Fig. 2. Under these conditions the circumstances of oscillation will be the same as in Fig 2, with the exception that it will now be horizontal. In Fig. 3, b is a strong spring which will bear 32 lbs. tension with a small increase in length; d is a sliding bar with

a cross-slot in which the crank c works and gives the bar a stroke 2a in length. If now the crank be rotated in the time t, that is in the time in which the spring and mass naturally oscillate, then the bar and the mass may oscillate in unison, and the spring b be stretched by the constant force of 32 lbs, so that an inextensible cord might take its place. As, however, all cords are elastic, they are properly represented by the spring b, and the arrangement in Fig. 3 corresponds with an indicator-drum acted upon by its spring, and connected by a cord with the cross-head of an engine.

If the crank be rotated in a greater or less time than t, the mass will be compelled to follow it, and, therefore, to change its period of oscillation and, in consequence, a change in the amplitude will occur. If the mass be made to oscillate in a time greater than t,

the force supplied to it at each point of its path must be less than the spring S would supply, which will be the case if the extreme left position t has shortened sufficiently to lower its tension to 31 lbs., and at the extreme right that it has lengthened so as to increase its tension to 33 lbs., while in the central position no change has occured; and suppose that the slight change in the position of the mass, due to the change in the length of b, be neglected so far as affects the tensions in S, so that the tensions in three positions may be taken as above calculated, i. e., at 22, 32, and 42 lbs.; then the force urging the mass to the right and causing the oscillation being the difference of the tensions of the springs, that is 31-22=9, 32-32=0, 33-42=-9 for the three principal positions and proportionate amounts for intermediate ones, which force will

require a time greater than t to produce an oscillation of the mass.

The effect on the amplitude will be to decrease it by an amount equal to the change of length in b, due to the change of tension from 31 to 33 lbs., which occurs during an oscillation; and in the same way, if the mass be forced to oscillate in a less time than t, the amplitude will be increased, the spring b being stretched to a greater tension than 32 lbs. at the extreme left, and to a less tension at the extreme right, so as to make the force actuating the mass greater than that required for an oscillation in the time t.

With an actual indicator and cord connection the change in amplitude will be greater or less as the cord is longer or shorter. Change of amplitude, however, is not particularly objectionable, providing

the motion of the drum remains a sufficiently exact reduction of the piston motion, which has been supposed to be the case the above treatment, so that all discussion of slight disturbances introducing harmonics has been avoided. The motion of the piston has also been supposed harmonic as represented in Fig. 3. When the piston motion is not harmonic, as is ordinarily the case, a long string will allow the drum motion to depart from the exact reduction of the piston motion so as to become more like the natural harmonic oscillation of the drum. With some engine having short connecting rods this would be a point requiring investigation as to the accuracy of the card if a long string connection were used.

It sometimes happens with a weak drum spring or a heavy drum that the latter oversteps

or throws; thus if the engine revolves in a less time than t, the force to produce oscillation in the mass m might be, for the left, centre, and right position in Fig. 3, 33-22=11, 32-32=0, 31-42=-11; but if the spring S is very weak, say only one tenth as strong as previously supposed, so that in the three positions its tensions are 2, 3 and 4 lbs. instead of 22, 32 and 42, there will be large difference to be made up by b. As the central tension S is 3 the average tension of b must be 3, so that in the central position the force acting on mass will be 3-3=0; but in extreme position to get the 11 lbs. required, b must be stretched at the left and shortened at right. At the extreme left b must be stretched until its tension is 13, so that 13-2 may =11, while at extreme right it must shorten until its tension becomes -7 so that -7-4 may =-11 as required; b will then be

under the compression, which is possible if b is a spring capable of being compressed; but if it is a cord, then as soon as the mass reaches a point to the right for which the cord tension becomes nothing, the cord will become slack under action of S alone. This will cause the drum to overstep, inasmuch as S alone is too weak to bring it to rest at the proper point.

The only difference between the drum with its spring and the arrangement shown in Fig. 3, is that in the latter we have a simple force urging a mass, while in calculating the action of the former the moment of the spring takes the place of the force, and the moment of inertia of the drum the place of its mass, leaving the action of the drum otherwise the same as that of a simple mass.

(b) Phase of the drum motion.

If friction be supposed between the mass

and its supporting plane, a change of phase will be produced and the oscillation of the mass will lag behind that of the sliding bar d, Fig. 3. This is plain when it is remembered that friction involves a transmission of energy from the crank C to the mass m, and that, therefore, b must be shorter during the stroke to the left and longer during that to the right, than it would be with no friction and the oscillation of m in unison with that of d.

The motion of an indicator drum is governed by the same law which controls the motion of a simple mass attached to a spiral spring. It was also shown that the drum and drum-spring have their natural time of vibration, which could, if desirable be made variable at will, either by altering the length of the spring or using inter-

changeable springs of different strength, or by varying the moment of inertia of the drum by attaching other masses to it.

(c) The Length of the diagram.

The amplitude of the drum motion was also touched upon, and it was shown by a simple arithmetical argument that if the engine forces the drum to oscillate in less than its natural time, the amplitude of its oscillation will be increased by an amount dependent on the elasticity of the cord or other connection; and in the same way, if the time be made greater the amplitude will be decreased.

The question of the change of amplitude will now be taken up more at length.

To make the treatment of the problem more general, the supposition that the spring b (Fig. 3.) is a very stiff spring will be abandoned and, to indicate that no such distinction is made between them,

the springs will hereafter be called S_1 and S_2.

Neglecting the masses of S_1 and S_2 and also the slight bending of the wire, two spiral springs can differ in their mechanical action only by exerting different forces for the same amount of extension.

Oscillation by a Single Spring.

Before discussing the oscillation of a mass by two springs the action of a single spring should be had clearly in mind. This is explained in works upon mechanics with more or less care and is treated in Rankine's Applied Mechanics, pg. 494; under the head "542 Straight Oscillation."

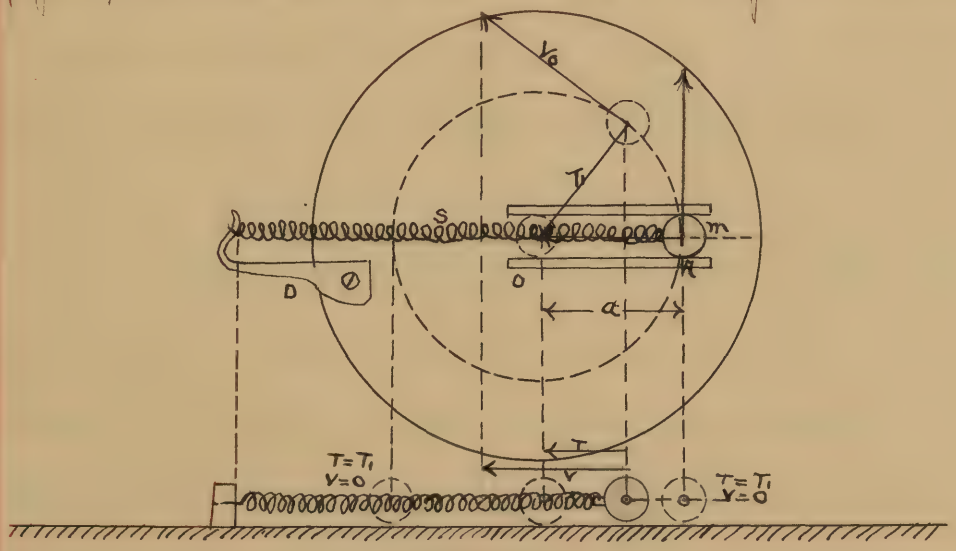


Fig. 4.

Let O (Fig 4) represent the face plate of a lathe upon which as mass m is guided to slide in a radial direction without friction. Let the spring S, be attached to the face plate at D so that its natural length brings the centre of the mass to the centre, O, of the face plate, as shown dotted.

When the lathe is not running m will remain at rest at O and to maintain it in any other position A, a distant from O, the lathe must be run at such a speed as will produce an exact balance between the centrifugal force, F; of m and the tension, T, of S,.

If w is the angular velocity (that is the linear velocity of a point at one foot from centre.) of the face plate the centrifugal force of the mass is

$$F' = m a w^2 \qquad (1.)$$

and, if f, is the number of pounds required to stretch the spring one foot (or ten times

that required to stretch it one-tenth of a foot), the tension for the distance a is

$$T_1 = a f_1$$

Equating these three results for equilibrium, when the centrifugal force due to the mass of the spring is neglected,

$$F' = T_1 = m\, a\, \omega^2 = a f_1 \text{ --------- (3)}$$

$$\therefore \omega^2 = \frac{a f_1}{a m} = \frac{f_1}{m} \text{ ---------- (4)}$$

As T_1 is proportional to a, it may be represented by the arrow marked T_1.

From the fact that a cancels out of the equation it is clear that, if the angular velocity of the face-plate be made equal to $\sqrt{\frac{f_1}{m}}$, the mass will remain balanced at any distance from the centre, a, at which it may be placed. For the time of one revolution, under these circumstances, there results from the definition of angular velocity:

$$t_0 = \frac{2\pi}{\omega} = 2\pi \sqrt{\frac{m}{f_1}} \text{ --------- (5)}$$

When a mass is oscillated in a right line by a spring, neglecting the mass of the latter

and other disturbances, the result is a simple harmonic oscillation, which is neither more nor less than the horizontal projection of the motion of the revolving mass and this projection furnishes all the facts of the oscillation.

The following are the correspondences in detail:

The semi-amplitude, a, of the oscillation equals the radius a.

The time of a complete oscillation is t_o, the time of a revolution, and is the same for any amplitude.

The motion of the oscillating mass is such that it is always directly beneath the revolving one.

The extreme tension (or compression) of the oscillating spring equals T_1, and the tension at any time is T, the corresponding horizontal projection of T_1, and this is, therefore, the accelerating force which controls the motion of the

mass. It is easily seen from this that this force is, as it should be, proportional to the distance of the oscillating mass from its mean position, or what is the same thing, to the elongation of the spring.

The velocity V at any time is the horizontal projection of the velocity V_0 of the revolving mass, therefore,

The greatest and least velocities are V_0 and 0.

Oscillation by two Springs.

Suppose that a second spring, S_2, be added as shown in Fig. 5.

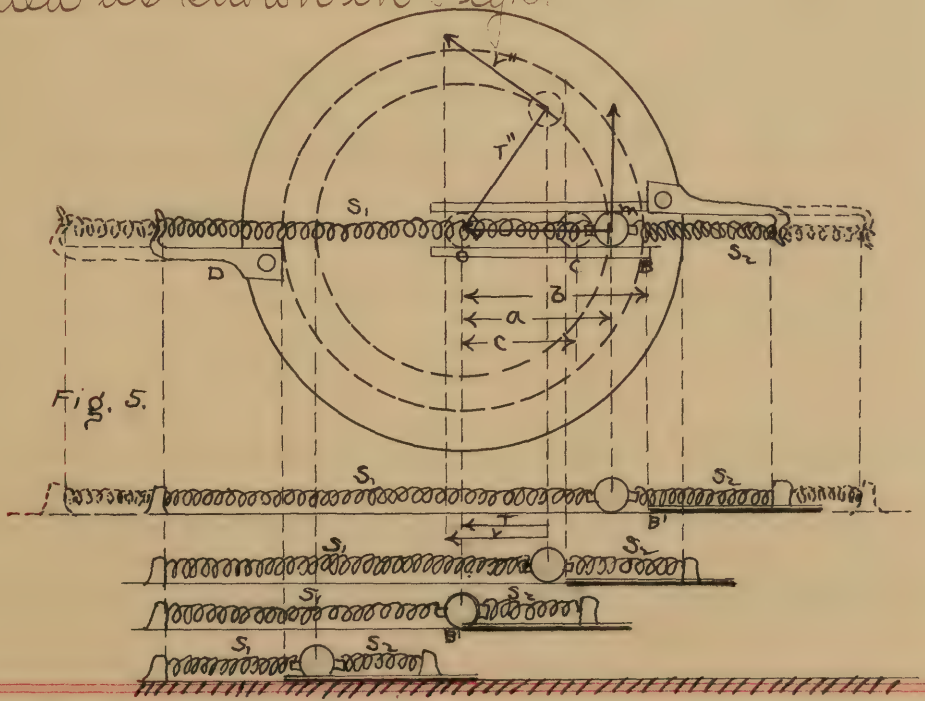


Fig. 5.

Let it be of such a length that the mass, when attached to S_2 only, will have its centre at B, distant b from O, as shown by the dotted circle. Suppose also, as before, that when m is attached to S, only its centre will be at O. When both springs are attached the mass will occupy an intermediate position, C, distant c from O, the value of c depending upon the strength of the springs. The position must be that in which the two springs pull with equal force, and, the elongations of S_1 and S_2 being respectively $CC = c$ and $BC = b - c$, this leads to the equation

$$\text{Force} = Cf_1 = (b - c)f_2 \text{ ------ (6)}$$

Which reduces to

$$c = \frac{f_2}{f_1 + f_2} b \text{ ------- (7)}$$

The position C is, therefore, that in which the mass will be at rest when the lathe is not running. If now the lathe be put in motion

centrifugal force will drive the mass further from O, and if the angular velocity be made equal to the value previously found for it, viz., $\sqrt{\frac{F}{m}}$, the mass will evidently take the position B, at which the tension of S_2 is zero. For greater velocities the mass will will be beyond B and for less it will be between C and B.

Let a be the distance of the mass from the centre for any angular velocity ω, then the equilibrium between the tensions and the centrifugal force is expressed by the equation

$$af_1 = (b-a)f_2 + m\,a\,\omega^2 \text{ ---------- } (8)$$

which reduces to

$$a = \frac{f_2}{f_2 + f_1 - m\omega^2} b \text{ ---------- } (9)$$

This equation shows what has been stated already, that when $m\omega^2 = f_1$, that is, when the centrifugal force is balanced by S_1 alone, $a = b$, while for less and greater values of ω, a will be respectively less and greater

than b. For $a > b$ S_2 will be compressed while for $a < b$ it will be stretched.

The mass is represented at the same distance from the centre as in Fig. 4, but that it may be in equilibrium at this point the velocity must be enough less (as indicated by the shorter arrow) to allow for the pull exerted by S_2.

To understand the motion of the mass in Fig. 3 it suffices to consider the horizontal projection of the arrangement just described, as was done in the previous case.

In the horizontal projections, Fig 5, a harmonic oscillation is supposed to be given to the piece B' so that its end B' oscillates with amplitude $2b$ about the central position. This piece takes the place of d, Fig. 3. its amplitude being called $2b$ in place of $2a$. The first and last horizontal projections show the extreme positions,

while the third shows the middle position, where the springs have their natural lengths; the second projection shows an intermediate position. The velocity and accelerating force at any point can be found as before by horizontally projecting the force and velocity of the revolving mass. The arrow representing the force can still be drawn from A to C by using a different scale to that previously employed, and it will represent the difference, T", of the tensions of the springs; while the varying length of its projection will represent the changing difference of tensions for the harmonic oscillation.

The Length of the Card.

The length of an indicator card is, therefore, given by the value of a in the last equation, where 2 will be the reduced length of the engine stroke, f_1 and f_2 respectively the number of pounds required to unwind a foot of cord from the

drum and to stretch the cord connection a foot (or ten times the force required for a tenth of a foot), ω the angular velocity of the engine, equal to $2\pi \div$ time of one revolution, and m the moment of inertia of the indicator drum divided by the square of the radius of the drum pulley expressed in feet and measured to the centre of the cord.

The only feature yet unexplained in Fig. 3 is that the springs therein are supposed to sustain an extra tension of 32 lbs., while in the horizontal projections of Fig 5, the springs are compressed when m is to the left of the centre. To put such a tension in the device Fig. 5, nothing more is necessary than to suppose the supports D and B to be extended, as indicated in dotted lines, by amount inversely proportional to the strengths of the springs. Thus let the left-hand end of S_1 be so extended a distance f_2 and the right-hand end of S_2 a distance f_1 then

the tension in each spring will be increased by the amount $f_1 f_2$ and, no matter where the horizontally oscillating mass may be, it will not feel the change because the difference of the tensions will remain unchanged.

By thus stretching the springs at their ends not attached to the mass; and by amounts proportional, instead of equal to f_1 and f_2, any desired constant tension may be added to the varying tension and compression so that the springs may be kept in tension throughout the whole oscillation, as is supposed to be the case in Fig. 3."

III The Design and Construction of the Machine.

Having now studied the theory of the drum-spring and knowing just what we want to test for, we are ready to begin the design of machine, which is to operate the Brown drum-testing device.

This device, (see R. Fig. 16), which was already made,

consisted essentially of a helical spring, a, which is interposed between the driving cord of the drum and the cross-head; [illegible] b, which gives it motion. The motion of the free end of the spring is communicated to a pencil point, C, through a multiplying bell crank lever, d. The pencil point marks on a piece of paper placed on the board, e, which for this purpose is swung into the required position. f is a connecting rod attached to the crosshead.

Since this machine was to be self-contained the best means of obtaining the motive power was by means of a motor. Knowing that the speed was not to be too high and power required not very great, I found that a one eight horse power General Elect. Motor, Type C, making 1400 rev. per. min. would answer the purpose very well. And with this speed I designed the rest of the part. The speed of cross-head of the testing device was to vary between 400

and 50 rev. per min. (But afterward used a small ½ horse power motor making 2400 rev. per. min. This motor was shunt wound and so arranged that by varying the resistance in series with the armature the speed could be kept constant at almost any rate, since the load is nearly the same at all times after the motor has come to speed.

Now knowing the speed of the motor (1400), which is higher than we want we have to reduce it down by means of pulleys and belts. The pulley on the motor being 2" diameter, then if that on the next shaft was 7" diameter, its speed would be $\frac{2}{7} \times 1400 = 400$ rev. per. min. which was that required.

This pulley was made of wood (see Fig. 14) and was fastened to its shaft by a set screw. The shafts (see Fig. 9+10) were made of wrought iron ½" diameter at ends and having a collar ¾" diameter left on them at the centre, this helped

to stiffned the shaft and also served to steady their motion when revolving.

The bearings (Fig. 6.) so designed as to be strong and not raised very high above the base, being 1⅛" from base to centre of shaft. In order to keep the speed constant a large cast iron fly wheel (Fig. 7.) was keyed on the first shaft.

This fly wheel was dish shaped so that the line of its centre of gravity will pass through the bearing, giving it very small bending arm and thus allowing a smaller shaft to be safely used. The weight of this wheel

$113.1^{\square"} - 50.27^{\square"} = 62.83^{\square"} \times 4" = 250.52$ cu. in.

$50.27^{\square"} \times \frac{1}{2}" = 25.14$ " "

$1^{\square"} \times 1" = 1$ " "

276.66 " "

.26#

165996

55332

71.9316 or 72#

To get its centre gravity take moments about one of the faces, thus:-

$2\times4''\times2''\times2=32$	$2\times4\times2=16$
$8\times\frac{1}{2}\times\frac{1}{4}=1$	$8\times\frac{1}{2}=4$
$1\times\frac{9}{7}\times1=1.1$	$1\times\frac{9}{7}=1.1$
34.1	21.1

$$21\overline{)34(1.62''}$$
$$\begin{array}{r} 21 \\ \hline 130 \\ 126 \\ \hline 40 \end{array}$$

∴ The centre of gravity is 1.6" from the face chosen. Now to investigate and see if the shaft is strong enough to this fly wheel. We have the bearing coming inside wheel. The centre of the bearing is $\frac{3}{4}$" or .75" from face of boss on wheel.

∴ The bending arm = .75" − (1.62 − 1.5) = .75" − .12" = .63"

and bending moment = 72# × .63" = 45.3#"

$$M=\frac{SI}{C}=S\frac{\pi d^3}{32}$$

$$45.3=\frac{5000\times3.14\times(\frac{1}{2})^3}{32}=$$

or $45.3=61.4$

showing that the shaft is plenty strong enough

and besides after the wheel had been finished and carefully balanced the wright was not much more than about 50 lbs.

The next thing to be done with this fly wheel, after it has been turned up and a half inch hole bored through the boss in centre, is to carefully balance it. In order to do this a shaft of ½" diameter and about 7" long is turned up in lathe and then drawn half way through the hole in the centre of wheel. Each end of this shaft is then placed so as to be able to run on two iron knife edges. These knife edges which should be in same horizontal plaine, were carefully leveled and fastened on two braches placed at about 4½" apart. Then the wheel with shaft is placed to rest on these knife edges and given a little push. The wheel will then roll and come to rest with the heaviest point lowest down. Then taking the wheel to the drill press and drilling some of the metal out from outside edge. Then taking

wheel back to the benches and repeating the same process, and continuing until the wheel will rest on the knife edges at any point where it placed. Or in other words when the wright of the wheel is equally spaced around its circumference. Having the wheel now carefully balance the shaft is driven out and a key way about $\frac{1}{8}$" wide by $\frac{1}{16}$" deep is cut along this hole in the wheel. The shaft upon which this wheel is to be fastened has a flat about $\frac{1}{8}$" filed on it. A key of the required dimensions and taper is then made of wrought iron.

Now this fly wheel and shaft having the speed of 400 rev. per. min. and in order to vary the speed of the second shaft, which operated the testing device, a couple of speed pulley could be designed so that the same belt would do for all of them.

One of these pulleys would be attached to the outside face of the fly wheel on the first

shaft, and the second pulley attached on second shaft by means of a chuck and so placed as to be in line with the first.

In designing these speed cones or pulleys we have (From Univ Machine Design 3/01)

The velocity of belt transmission.

Over 1st. pulley $\pi d_1 N_1 = V$

2nd. $\pi d_2 N_2 = V$

$\therefore \frac{d_1}{d_2} = \frac{N_2}{N_1}$ (A)

Where d_1 is the diameter of 1st. pulley.

d_2 " " " " 2nd. "

N_1 " " number of rev. of 1st.

N_2 " " " " " 2nd.

The equation (A) is only strictly true when the belt is infinitely thin. When the belt has a thickness δ, the effective diameters of the pulleys are $d_1 + \delta$, and $d_2 \delta$.

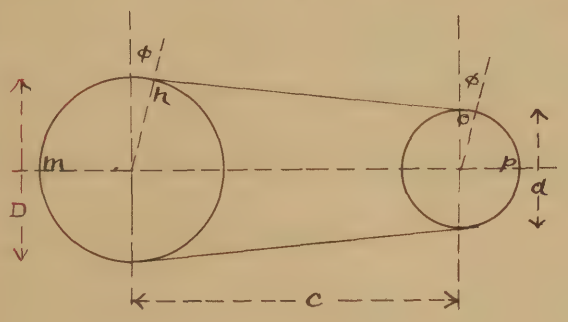
Then (A) becomes

$$\frac{N_2}{N_1} = \frac{d_1 + \delta}{d_2 + \delta} \qquad (1\text{A})$$

But this belt thickness is generally so small compared with pulley diameter that it may be neglected without any great

error.

Length of belt — open — ϕ depends on $D + d$. Hence if Σ and C are constants for two or more pair of pulleys, the same belt will run on any pair of pulleys of the set.



Let D and d be diameters of two pulleys in inches C, their distance apart L, the length of belt.

$\Sigma = D + d$

$\Delta = D - d$

$L = 2(mn + no + op)$

$= (\frac{\pi}{2} + \phi) D + 2c \cos.\phi + (\frac{\pi}{2} - \phi) d$

$= \frac{\pi}{2}\Sigma + \phi\Delta + 2c \cos.\phi$

$\sin\phi = \frac{\Delta}{2c}$; $\cos. \sqrt{(1 - \frac{\Delta^2}{4c^2})}$

For an open belt ϕ is generally small, so that

$\phi = \sin\phi$, very nearly.

$\therefore L = \frac{\pi}{2}\Sigma + 2c \left\{ \frac{\Delta^2}{4c^2} + \sqrt{(1 - \frac{\Delta^2}{4c^2})} \right\}$

$= \frac{\pi}{2}\Sigma + 2c \left\{ 1 + \frac{1}{8}\frac{\Delta^2}{c} \right\}$ nearly

For open belts run on one pair pulleys the sum and difference of whose diameter are Σ,

and Δ_1 and for a second pair of pulleys. Σ_2 and Δ_2, and since the length of belt is the same in the two cases,

$$\frac{\pi}{2}\Sigma_1 + 2c\left\{1 + \frac{1}{8}\frac{\Delta_1^2}{C^2}\right\} = \frac{\pi}{2}\Sigma_2 + 2c\left\{1 + \frac{1}{8}\frac{\Delta_2^2}{C^2}\right\}$$

$$\Sigma_2 = \Sigma_1 + \frac{\Delta_1^2 - \Delta_2^2}{2\pi c}$$

In designing these speed cones or pulleys we have (From Unwin Machine Design page 373)

For open belts

Let $\Delta_1 = D_1 - d_1$; $\Delta_2 = D_2 - d_2$; $\Sigma_1 = D_1 + d_1$; $\Sigma_2 = D_2 + d_2$. (1)

Where $D_1 + d_1$ = dia. of 1st. opposite pair pulleys on 1st + 2nd shafts respt.

$D_2 + d_2$ = " " 2nd " " " "

Then $\frac{D_1}{d_1} = \frac{n_1}{N}$ (2) where N is speed of 1st shaft, n_1, n_2, n_3 ect. = required speeds for the second shaft by means of the respective pulleys

and $\Delta_2 = D_2 - d_2 = \frac{n_2 - N}{N + n_2}\Sigma_1$ nearly (3.)

Then from equation (7) on page 370

$\Sigma_2 = \Sigma_1 + \frac{\Delta_1^2 - \Delta_2^2}{2\pi c}$ (4) c is distance between the centres of the two shafts

and $\frac{D_2}{d_2} = \frac{n^2}{N}$ (5)

Hence, more exactly,

$$\left.\begin{aligned} D_2 &= \frac{n_2}{N+n_2}\Sigma_2 \\ d_2 &= \frac{N}{N+n_2}\Sigma_2 \end{aligned}\right\} \quad (6.)$$

Then applying the above formula.

$N = 400$ n_1 should $= 400$

n_2 " $= 200$

n_3 " $= 100$

Then from (1)

$\Delta_1 = 6-6 = 0$ $\Sigma_1 = D_1 + d_1 = 6+6 = 12$

From (3)

$$\Delta_2 = D_2 - d_2 = \frac{n_2 - N}{N+n_2}\Sigma_1$$

$$4 - d_2 = \frac{200-400}{600}\,12 \qquad \Delta_2 = 4-8 = -4$$

$$d_2 = 4+4 = 8$$

$$\Sigma_2 = \Sigma_1 + \frac{\Delta_1^2 - \Delta_2^2}{2\pi c} = 12 + \frac{0+16}{2\times 3.14\times 10} = 12 + .25$$

$$D_2 = \frac{n_2}{N+n_2}\Sigma_2 = \frac{200}{600}\times 12.25 = 4.08 = 4\tfrac{1}{16}''$$

$$d_2 = \frac{N}{N+n_2}\Sigma_2 = \frac{400}{600}\times 12.25 = 8.16 = 8\tfrac{1}{8}''$$

And for third pair.

$$\Delta_3 = D_3 - d_3 = \frac{n_3 - N}{N+n_3}\Sigma_1$$

$$2 - d_3 = \frac{100-400}{400+100}\times 12 = \frac{-300}{500}\times 12 \qquad \Delta_3 = D_3 - d_3 = 2 - 9\tfrac{1}{5} = \tfrac{10}{5} - \tfrac{46}{5} = \tfrac{-36}{5}$$

$$d_3 = 2 + \tfrac{36}{5} = 2 + 7\tfrac{1}{5} = 9\tfrac{1}{5}$$

$\Sigma_2 = \Sigma_1 + \frac{\Delta_1^2 - \Delta_2^2}{2\pi C} = 12 + \frac{(\frac{36}{5})^2}{2 \times 3.14 \times 10} = 12 + .65 = 12.65$

$D_3 = \frac{n_3}{N + n_3} \Sigma_3 = \frac{40}{500} \times 12.65 = 2\frac{7}{16}$" (about)

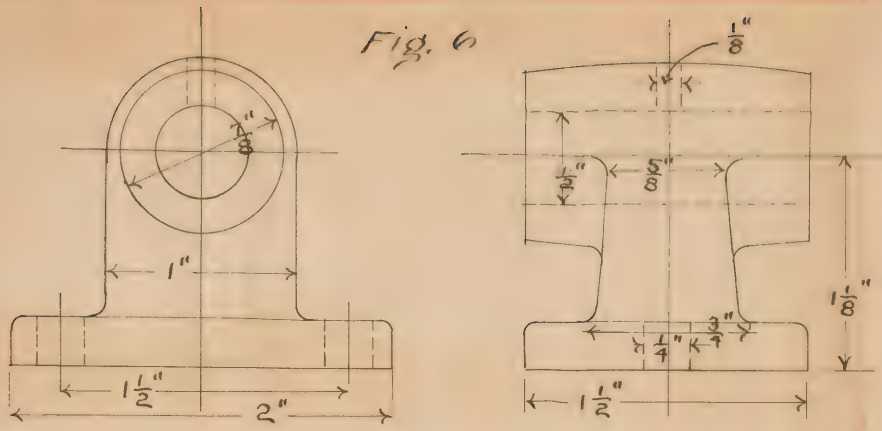
$d_3 = \frac{N}{N + n_3} \Sigma_3 = \frac{460}{500} \times 12.65 = 9\frac{3}{4}$"

These pulleys were made of wood and are shown in Fig. 13 and 15. There is an extra groove on pulley Fig. 15, which is used in running a belt connected to the Tachometer (B in Fig. 16). This groove is the one whose diameter is 8".

The crank disk (Fig. 8) which is made of cast iron is fastened to the second shaft. This crank disk has three $\frac{3}{8}$" tapped holes on it of different distances from the center, so that the length of stroke can be varied. These lengths being about that which are given to an indicator when connected to an engine. The wrought iron pin is shown in Fig 12.

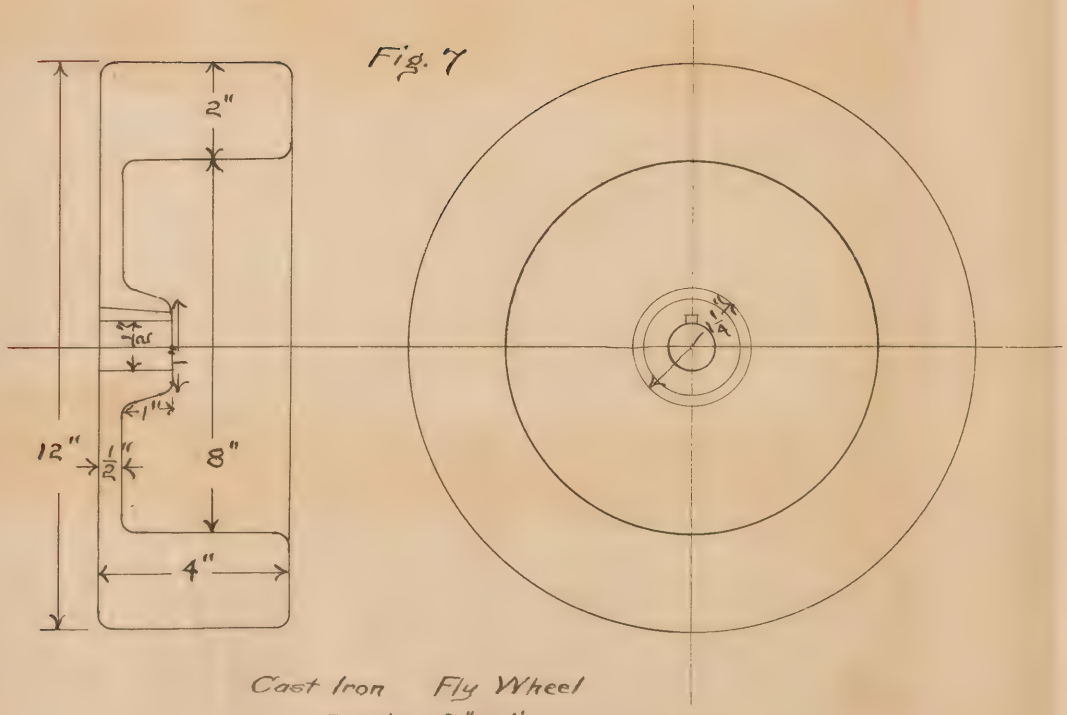
The completed machine is shown in Fig. 16.

Fig. 6



4 Cast Iron Bearings
Full Size

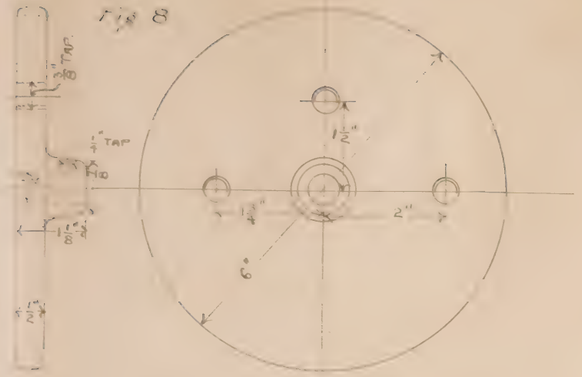
Fig. 7



Cast Iron Fly Wheel
Scale 3" = 1'

Detail of Drum Spring Testing Machine.

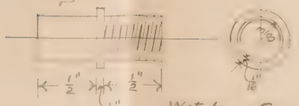
Fig. 8



Cast Iron Crank Disk

1/2 Size

Fig. 11



Wrt. Iron Crank Pin

Full Size

Fig. 12

Brass Bushing for Crank Pin

Full Size

Fig. 13

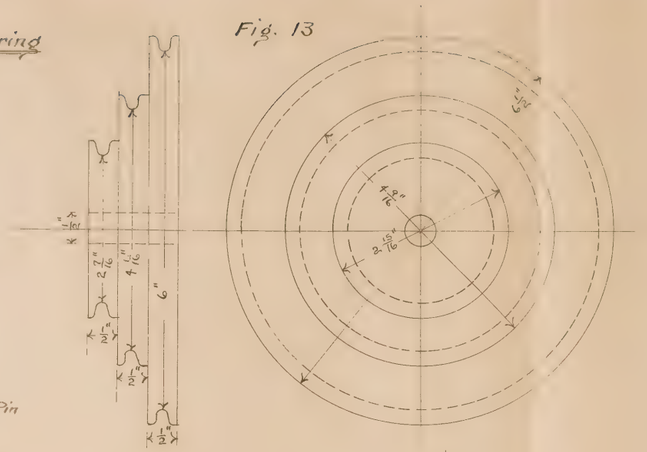


Fig. 14

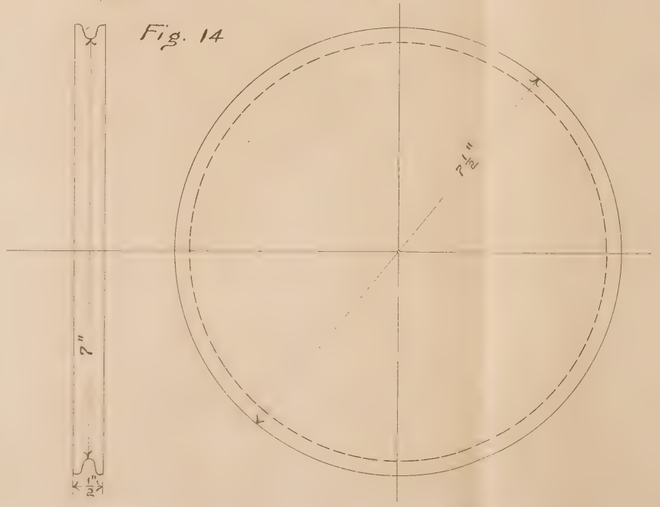
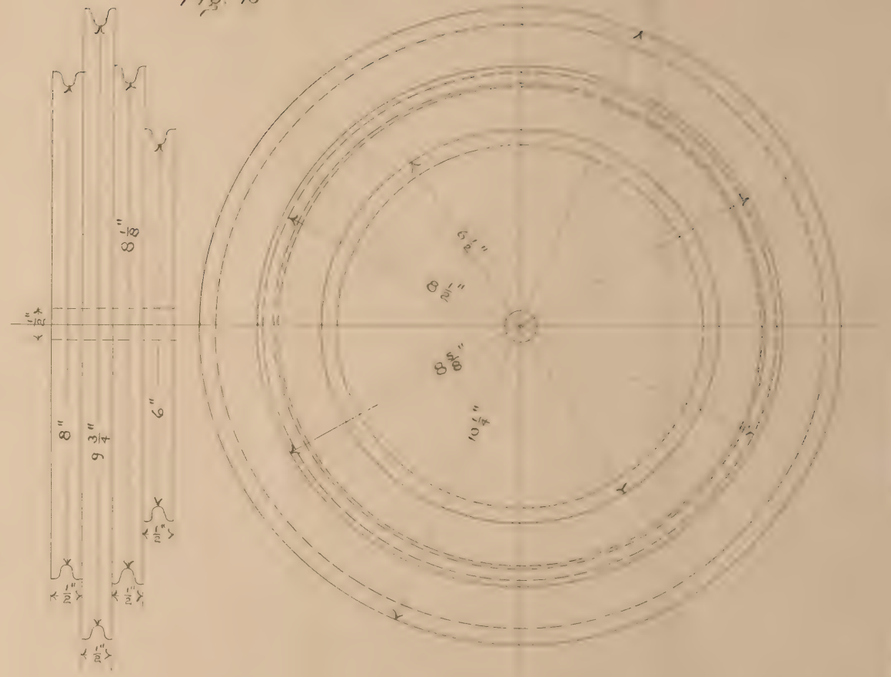


Fig. 15



Wooden Pulleys

1/2 Size

Fig. 9

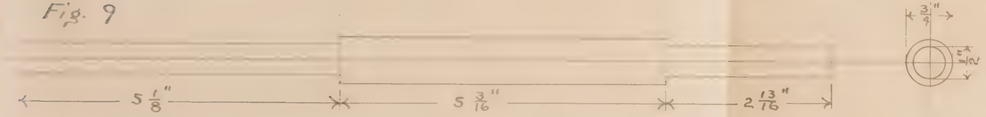


Fig. 10

Wrt Iron Shafts

1/2 Size

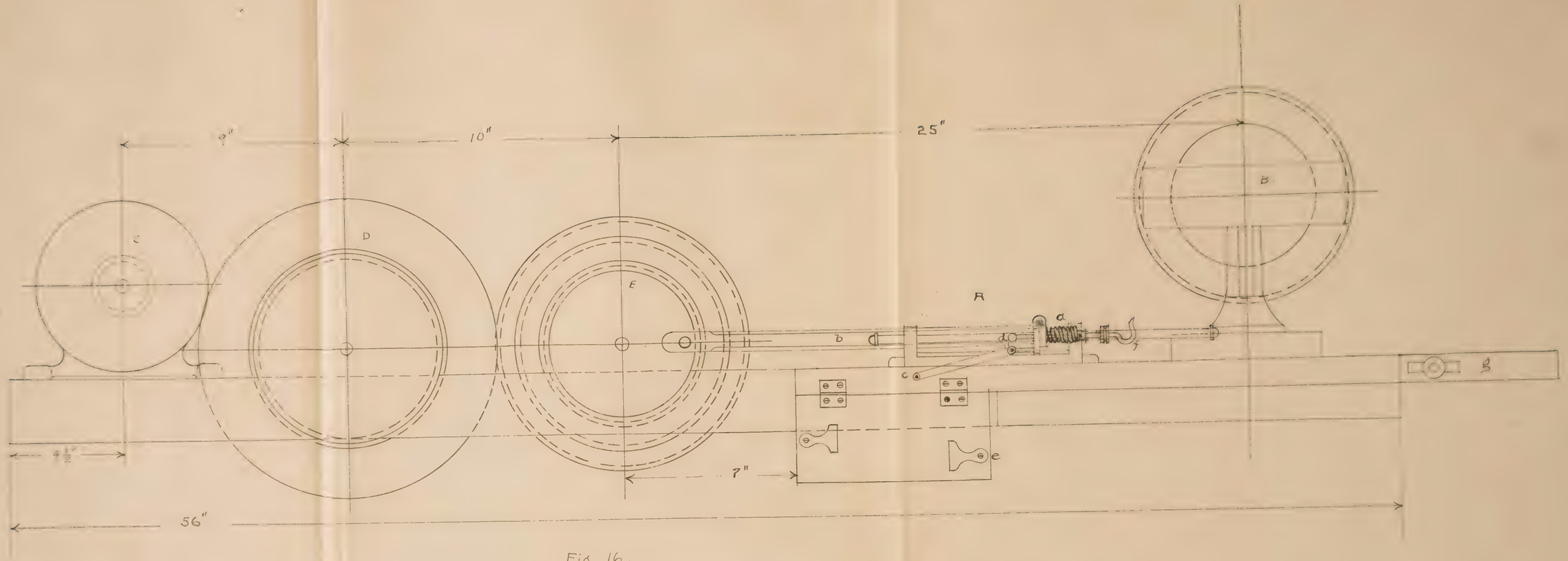


Fig. 16.

Scale 3" = 1'

IV. Method of Conducting the Test.

Knowing now what we are to test for, and having our machine built we are ready to begin the test.

An indicator is fastened in the clamp (shown in Fig. 16-A-g). The string which is wound around the drum, is led through a guide pulley and fastened over the hook carried by spring at a. Then the motor is started and as soon as its sped has become constant the board, e, carrying a card is pressed against the pencil point and a card taken. This is done for a number of speeds until the best sped is obtained. The best sped is that in which the tension on the drum spring remains constant during the stroke. This is told from the card when the two long lines of the loop are parallel to themselves and to the base line, or nearly so. The base line or zero line is the line taken when there is no tension on the spring, that

is when the indicator is detached.

Now in starting a test a certain tension is put on the drum-spring. The string connection made and the motor started. Cards are taken and the sped varried, enough time being given between each varriation for the speed to become constant, until finally the best sped is high enough to register on the Tachometer its reading taken, but if the speed is not high enough the number of revolution per. minute must be noted by means of a hand revolution counter and a watch. This same process is repeated for different tensions on the drum spring, not forgetting to take the zero line for each card. Also the effect of the higher speeds was noted in several cases. The length of the stroke should always be noted, this was 4" in my case as I did not have enough time to see what effect the varriation of this length would have on the drum springs.

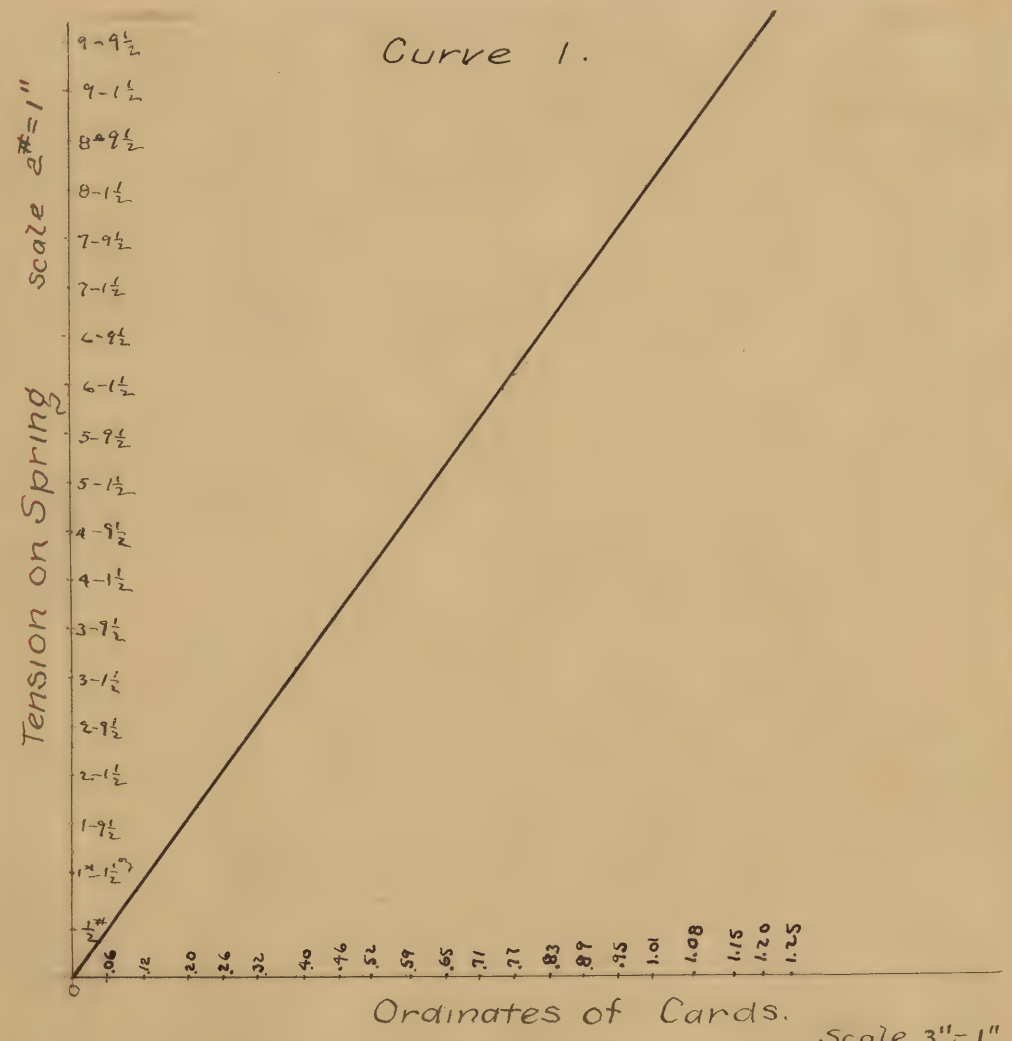
V Calibrations of Instruments.

The only instruments which needed to be calibrated on the machine were, first the helical spring (a) of the Brown Drum Spring tester and second the Tachometer.

Now inorder to calibrate the spring on the testing device, it was taken off of the machine and fastened up to a board so as to be in a vertical position. A card was fastened in the clamps of board, c, and with no tension on spring a stroke described by pencil point on card. This is the zero tension. Then certain known weights were attached to hook on spring and starting point of each stroke noted. This was done for about every half pound tension. The greatest tension being about ten pounds, which gave nearly two inches deflection of the pencil point from its zero position. Then a curve is plotted with tensions in lbs as ordinates and pencil deflection in inches as abscissas. (Curve 1.)

Calibration of Spring on Brown's Tester.

Tension on Spring (lbs)	Height of Ordinate on Card (inches)	Tension on Spring (lbs)	Height of ord on Card (inches)	Tension on Spring (lbs)	Height of ordinate on Card (inches)
0 # 0 oz	0	3 # – 9½ oz	.46"	7 # – 1½ oz	.89"
½	.06"	4 – 1½	.52	7 – 9½	.95
1 – 1½	.12	4 – 9½	.59	8 – 1½	1.01
1 – 9½	.20	5 – 1½	.65	8 – 9½	1.08
2 – 1½	.26	5 – 9½	.71	9 – 1½	1.15
2 – 9½	.32	6 – 1½	.77	9 – 9½	1.20
3 – 1½	.40	6 – 9½	.83	9 – 15½	1.25



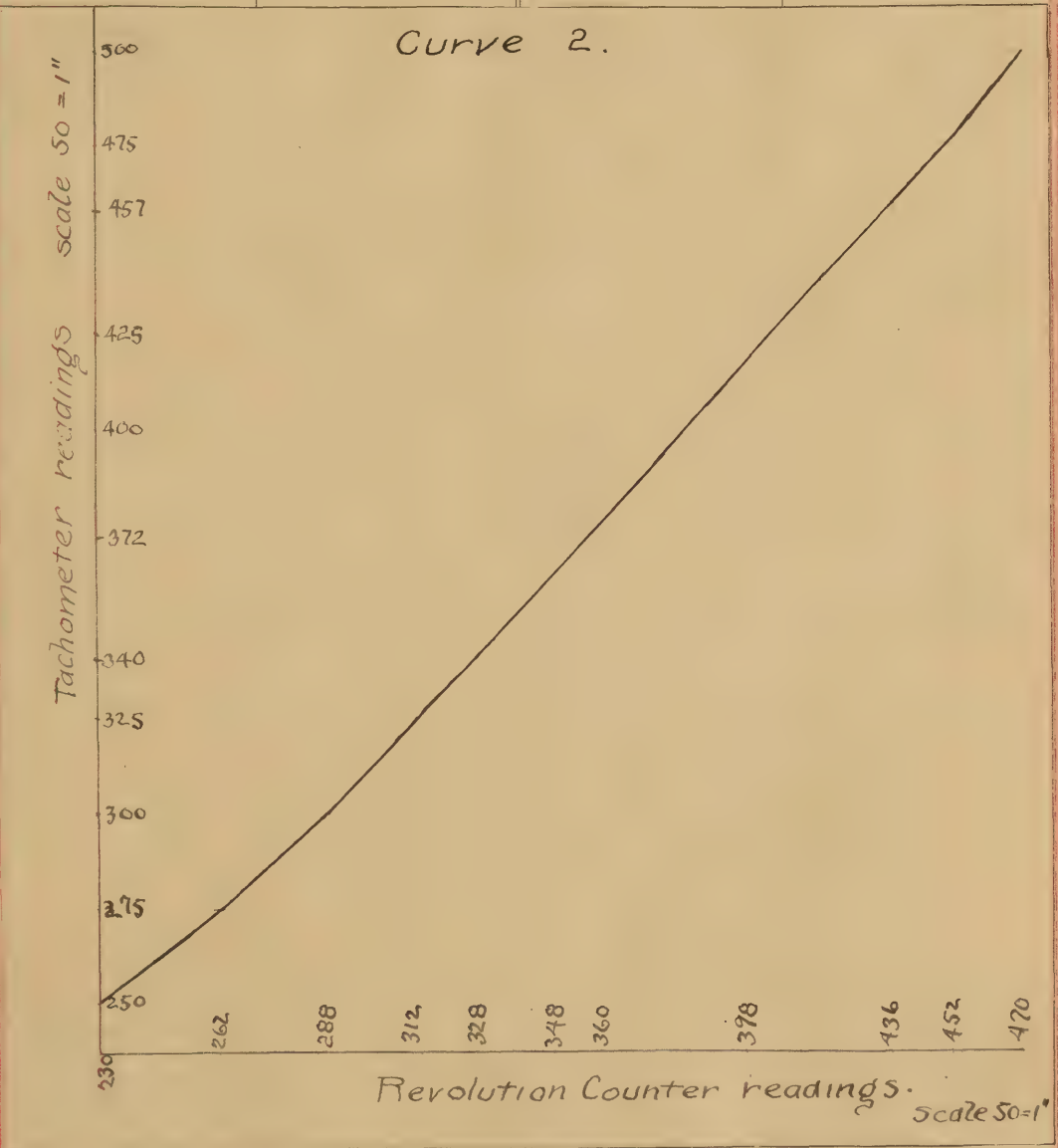
To calibrate the Tachometer, the motor is started and belts arranged on pulleys so that the Tachometer just registers. Then when the speed has become constant note the number of revolutions of the second shaft per minute by means of the revolution counter and a watch, and also taking the Tachometer reading. The speed is then increased about 20 or 25 more revolutions per. minute and the same process repeated. The same is repeated up to a speed of about 500 rev. per. min. This being higher than any speed that I used.

Then a curve for this instrument was plotted with Tachometer readings as ordinates and the true number of revolutions of the second shaft, that is the number of strokes of the cross-head of testing device, per. min. as abscissas. This is curve # 2.

Calibration of Tachometer.

Tach. readings	Counter read. rev. per. min.	Tach. readings	Counter read. rev. per. min.
250	230	400	360
275	262	425	398
300	288	457	436
325	312	475	452
340	328	500	470
372	348		

Curve 2.



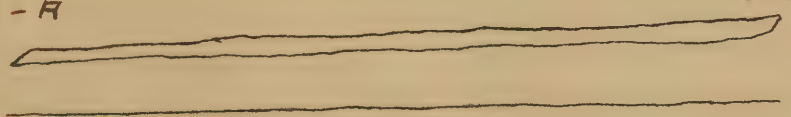
VI Observations.

Cards were taken for the best speeds at different tensions of the drum springs of the three types of indicators. These types of indicators were (A) Tabor indicator, the drum spring of which is a flat spiral steel spring; (B) the Thompson indicator, which has a similar kind of spring to that of the Tabor indicator; and (C) the Crosby indicator, the drum spring of which is a helical spring similar to the indicator spring used above the piston. Different tensions could be put on these springs by twisting one end of these springs, the other end is fixed.

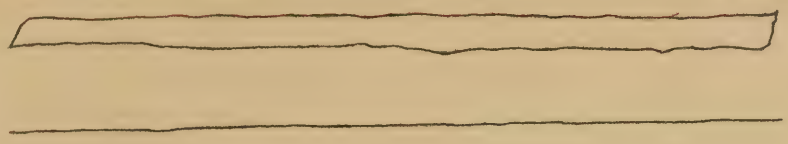
Cards

Type A

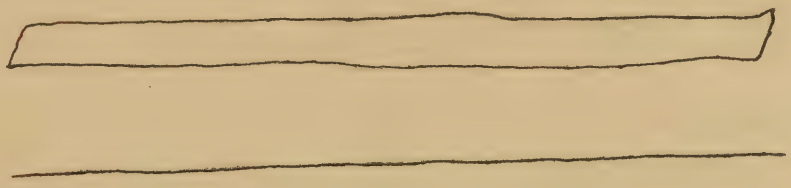
#1 - A



#2 – A 182 rev. per min



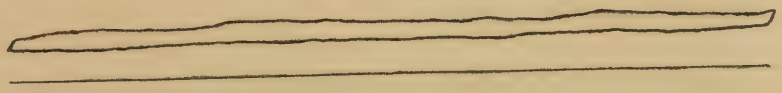
#3 – A 196 rev. per min



Type B.

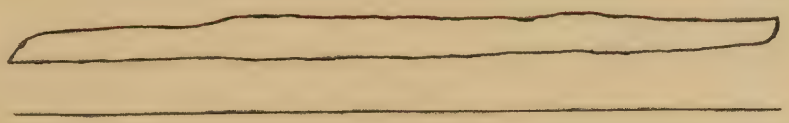
#1 – B 38 rev. per min

#2 – B 48 rev. per min



#3 – B. 66 rev. per min

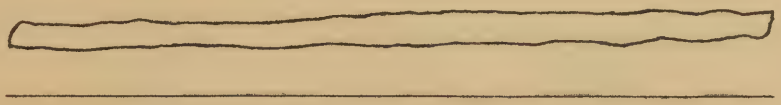
#4 - B 84 rev. per min



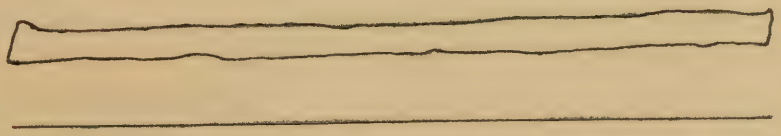
Type C

#1 - C 100 rev. per min

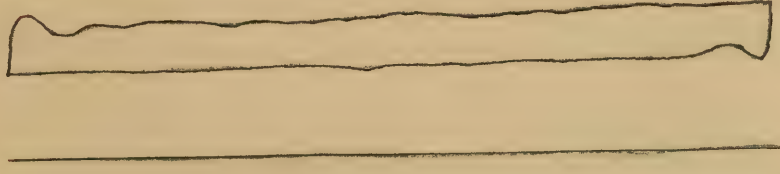
#2 - C 130 rev. per min



#3 - C 140 rev. per min



#4 - C 144 rev. per min



The effect on the diagram of a higher speed than best speed for the certain drum spring tension can be plainly seen in the following card taken with a couple of the indicators. Showing what the effect will be if the engine rotates too fast for the drum spring tension. That is the time of oscillation of the drum not being the same as that of the engine.

#5-B

250 rev. per min by tachometer

#6 - B

325 rev. per min.

#7 – B

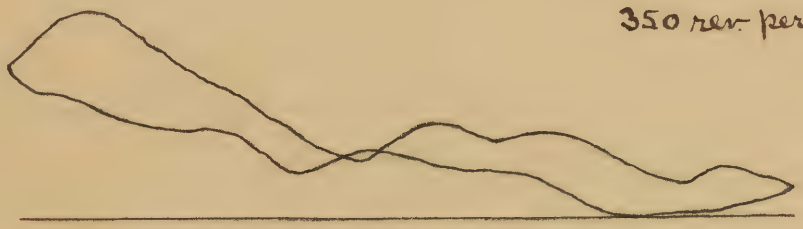
132 rev. per min

#8 – B

275 rev per min

#9 – B

350 rev. per min



#5 – C

300 rev. per min

2 1/4 turns of drum spring.

#6 - C

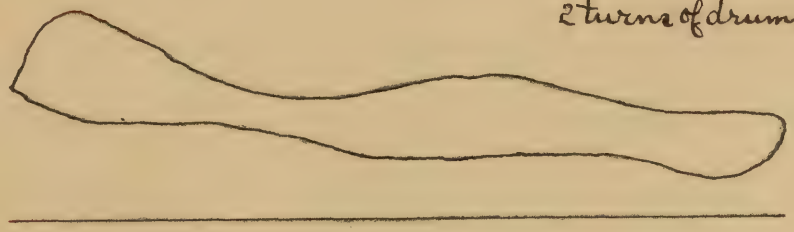
405 rev. per min

2 1/4 turns of Spring

#7 - C

345 rev per min

2 turns of drum-Spring



#8 - C

440 rev-per-min.

#9 - C

482 rev. per min

VII. Results

The results obtained from these test are shown in following table.

Number of Card	Tension on Drum-Spring (in lbs.)		Best Speed (in rev. per min.)
	Highest.	Lowest.	
#1 - A	3.6#	2.1#	122
#2 - A	4.6	3.1	182
#3 - A	6.2	4.0	196
#1 - B	1.0	.5	38
#2 - B	2.5	1.4	48
#3 - B	3.1	2.0	66
#4 - B	4.2	2.2	84
#1 - C	2.0	.25	100
#2 - C	3.7	2.1	130
#3 - C	4.1	2.1	140
#4 - C	6.1	3.8	144

A - Tabor indicator # 1185.
B - Thompson " # 3071.
C - Crosby " # 7051.

VIII. Conclusions.

In concluding I must say that I did not have as much time in testing the drum springs as I would like to have had. Having to make but a few hurried test and thus not being able to give it very much study. Nevertheless I learned that for any tension on the drum spring, there is always a corresponding speed of the engine at which the greatest varriation of the spring tension is a minimum, practically constant on each stroke. When the speed of the engine is too high for the tension of spring the indicator cord and drum will first receive a jerk from the engine, which will make the drum over step due to its inertia. This causing the driving cord of the indicator to whip, that is it is tight at one moment and very loose at the next. This will cause an error in the length of the indicator cards. And it is shown by the great varriation of tensions on the Brown Tester cards.

In the testing of the springs of the three types of indicators I found their best speeds for different tension on the spring. In all cases the speed increase as the tension increases. The Crosby indicator drum spring appeared to give the least variation of tension at higher speeds.

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